A First Search for Solar ^8B Neutrino in the PandaX-4T Experiment using Neutrino-Nucleus Coherent Scattering

马文博

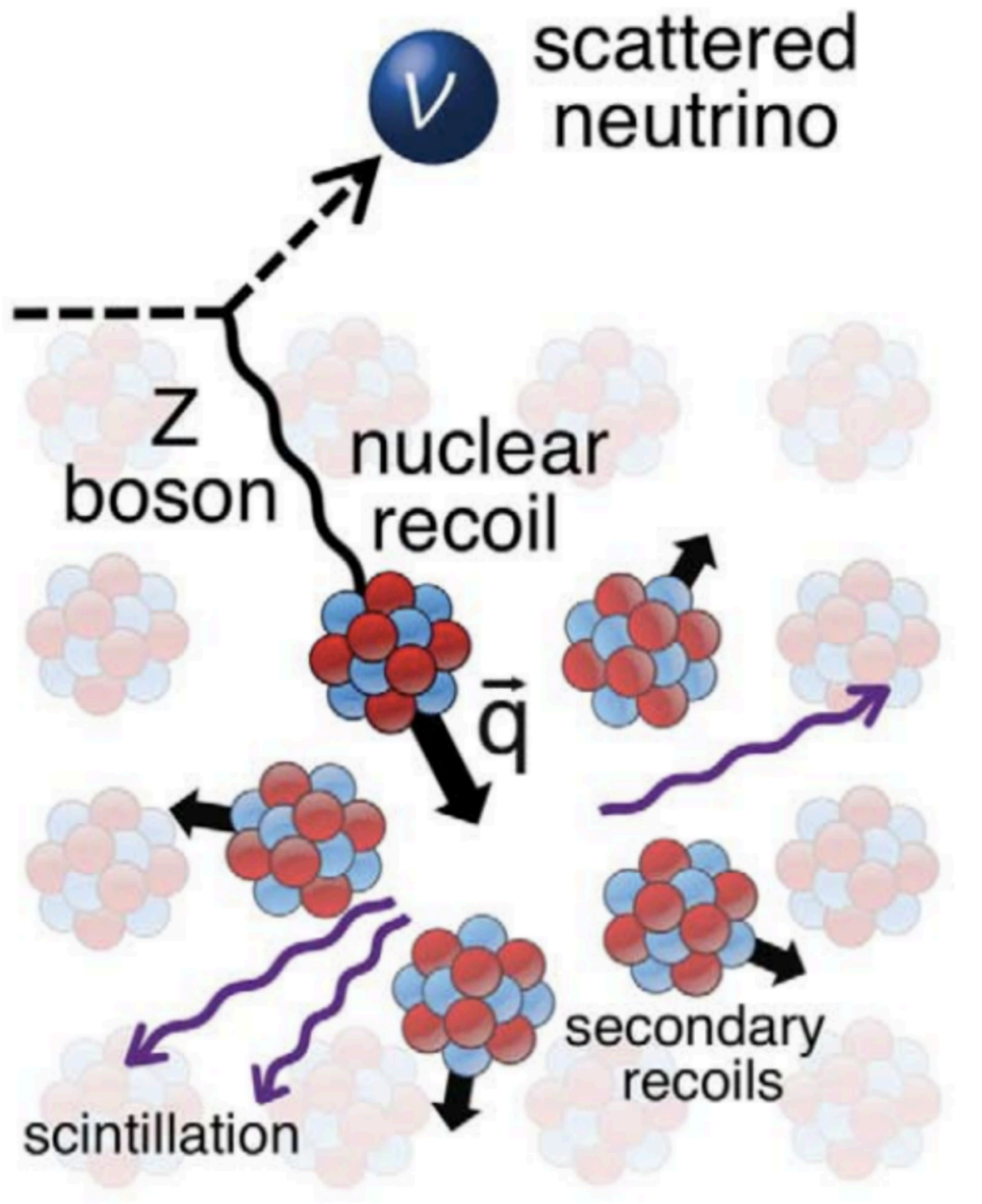
wenboma@sjtu.edu.cn

arxiv 2207.04883

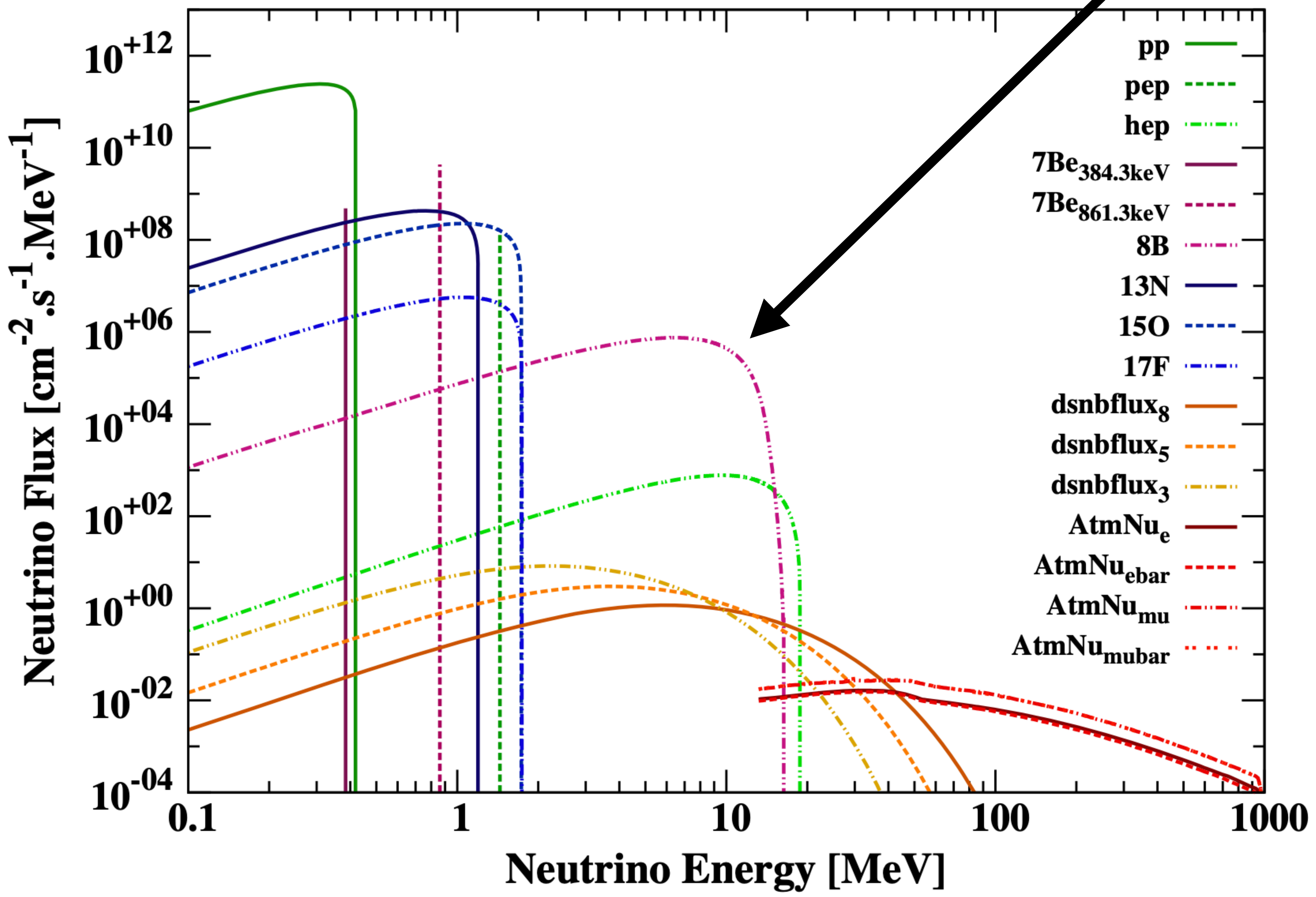
Introduction

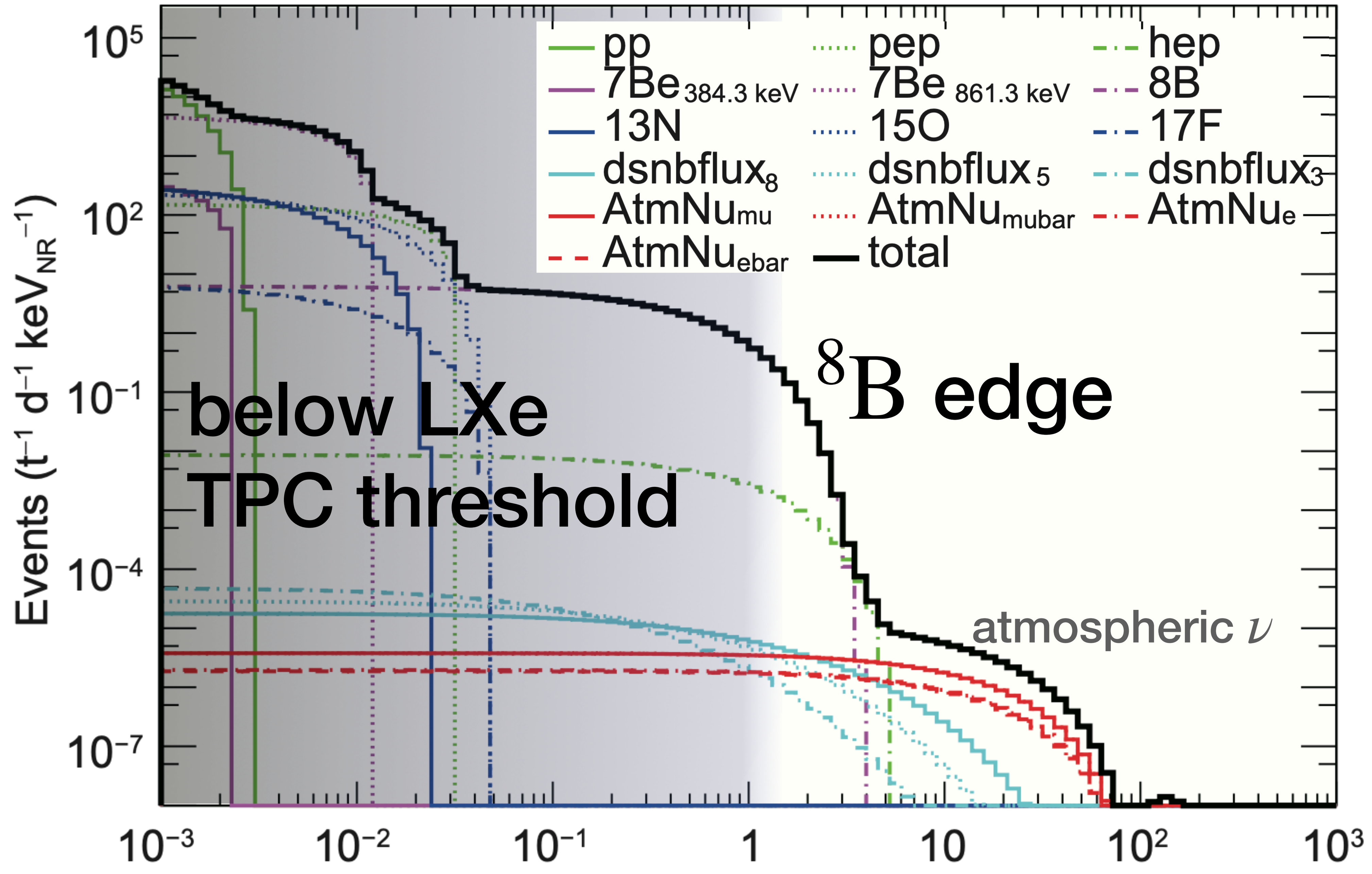
- Coherent elastic neutrino-nucleus scattering (CEvNS)
- Boron-8 neutrino deposits several keVnr energy in the LXe TPC
- Mimic 6 GeV WIMP (neutrino floor)

solar $^{8}B\ \nu$ $\boxed{^{8}\mathrm{B} \rightarrow {}^{8}\mathrm{Be}^{*} + e^{+} + \nu_e}$



10.1126/science.aao0990

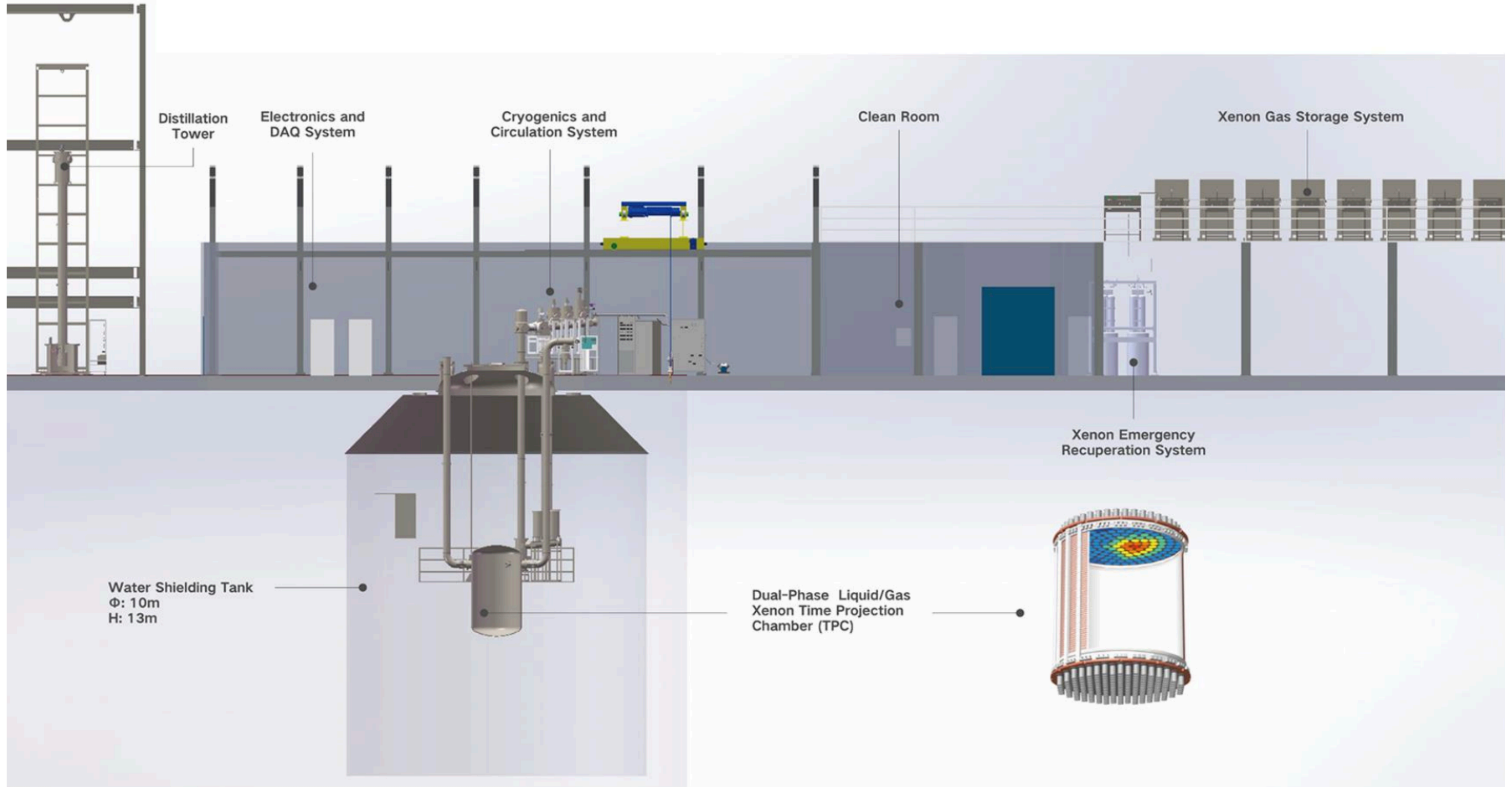




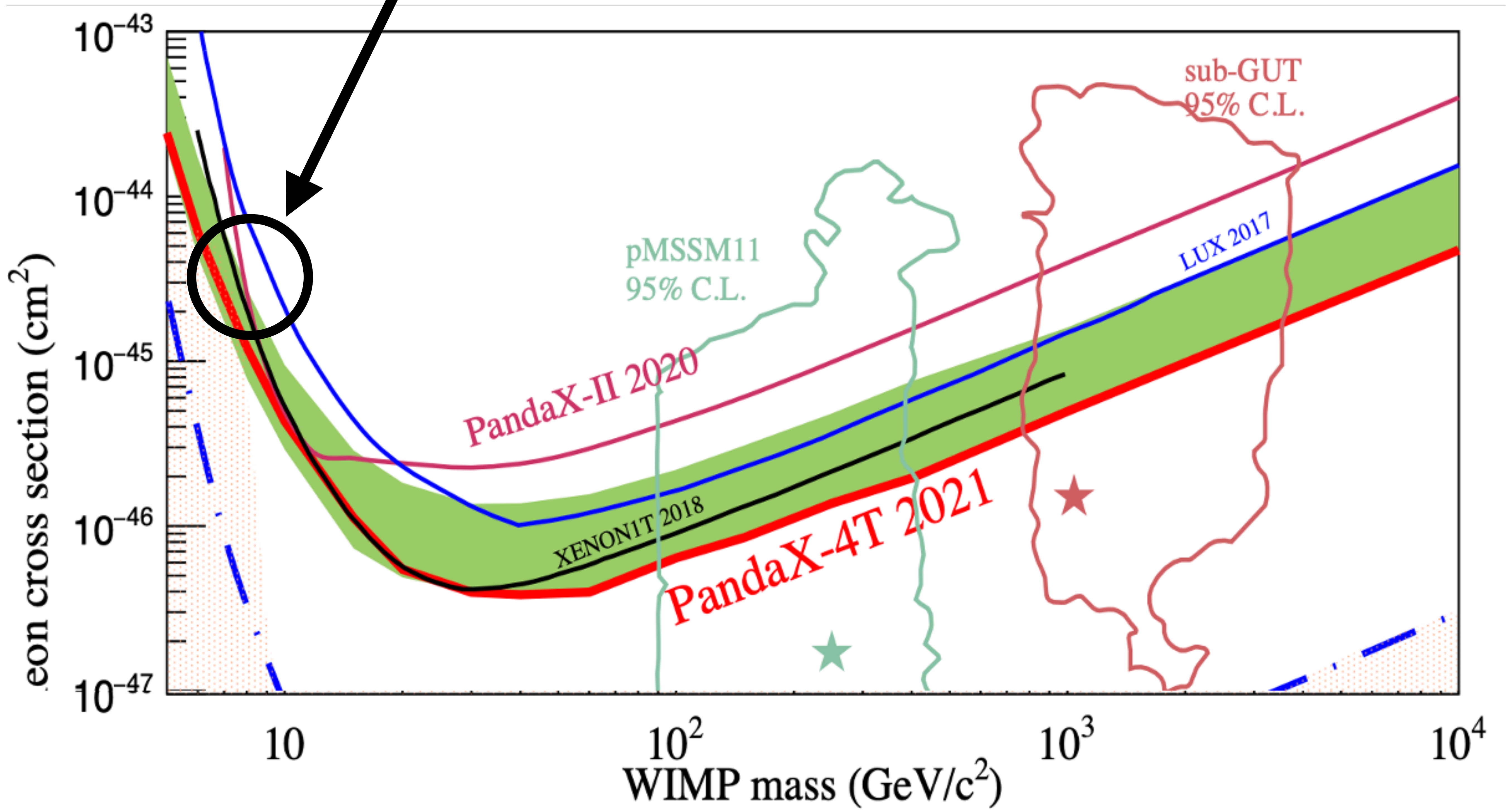
Recoil energy in liquid xenon

PandaX–4T Experiment

- Underground Xe detector located at China JinPing underground Lab
- Best WIMP constrain in 2021, touching low-energy neutrino floor
- Multi-purpose detector for dark matter and other rare events



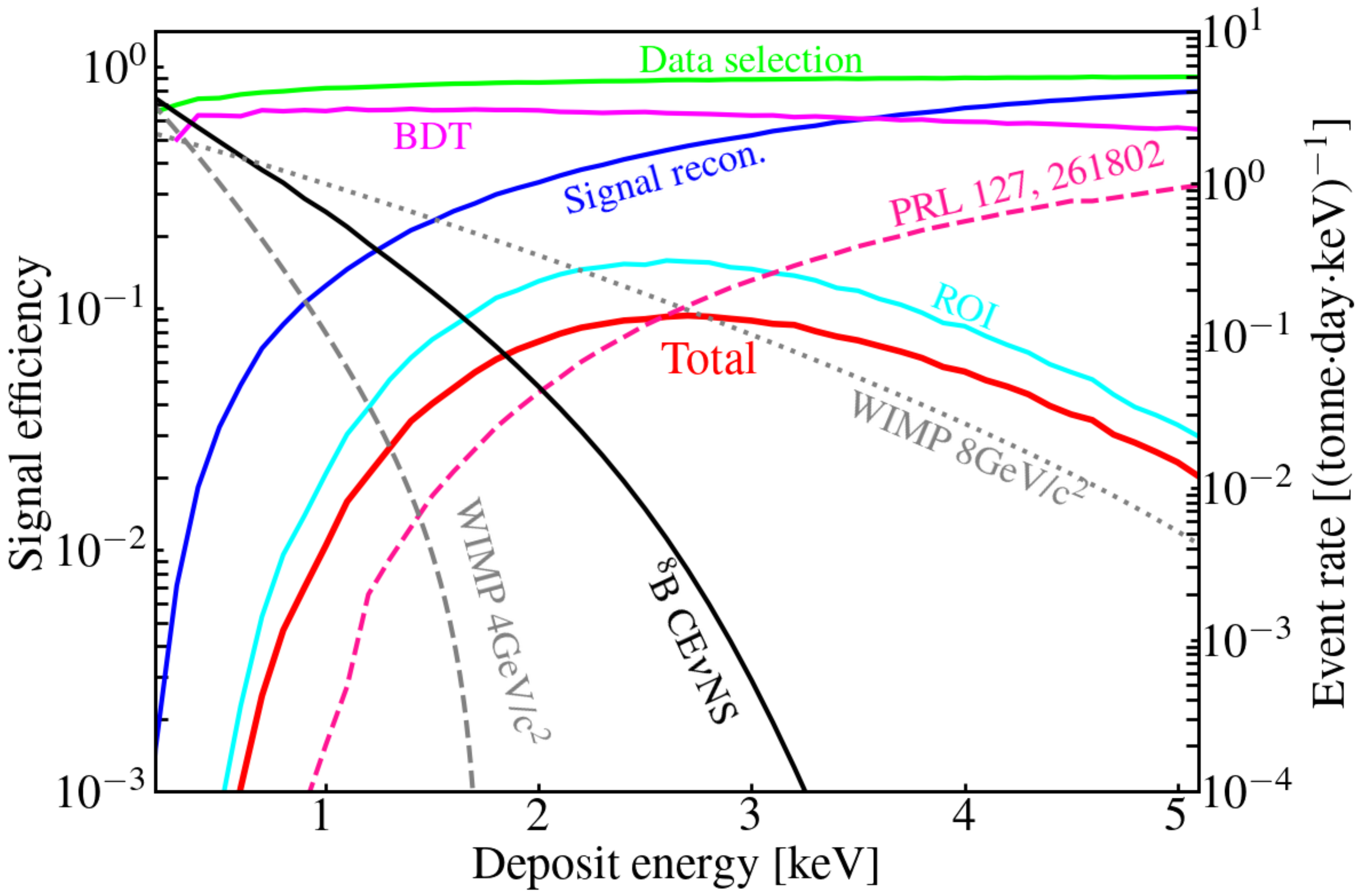
Touching neutrino floor



Low–threshold improvement and detection efficiency

- $^{8}\nu$ CEvNS is a sharp cliff
- Various techniques are made for lowering analysis energy threshold
- Efficiency calculated by waveform simulation

- S1: 2 PE -> 0.3 PE, 2 or 3 photon
- S2: 80 PE -> 65 PE, ~ 3.2 electron



- Signal reconstruction
- Deadtime
- Quality cuts
- BDT in ROI

Data processing

- Low-level detector response is crucial for searching 8B
- Discriminate physical events out of noise
- Cuts suppress background
- Validated the complete process using data-driven waveform simulation

Photon detection (arxiv 2108.03433) → *waveform* → **Software BLS** → *hit* → **Hit clustering** → *signal* → **Signal tagging**

- Low level efficiency

S1,S2,others → **Physical S1/S2 identification** → *event* → **Event build**

- Correctly identify S1-S2 pair out of dark noise, random electrons, sparking...

→ **Deadtime** → **Quality cut** → **BDT cut** → **Final candidates**

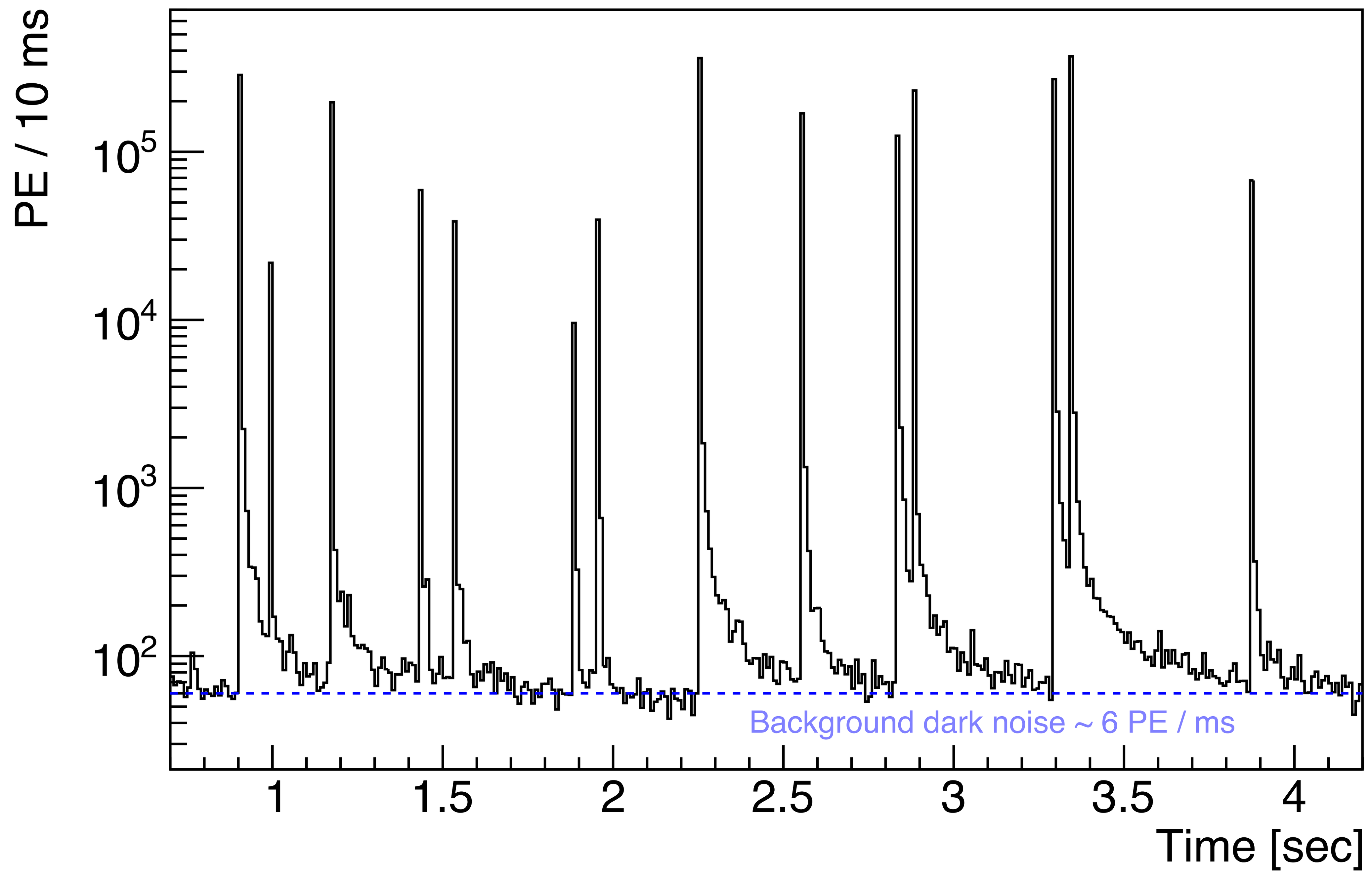
Deadtime:
- Reduce exposure

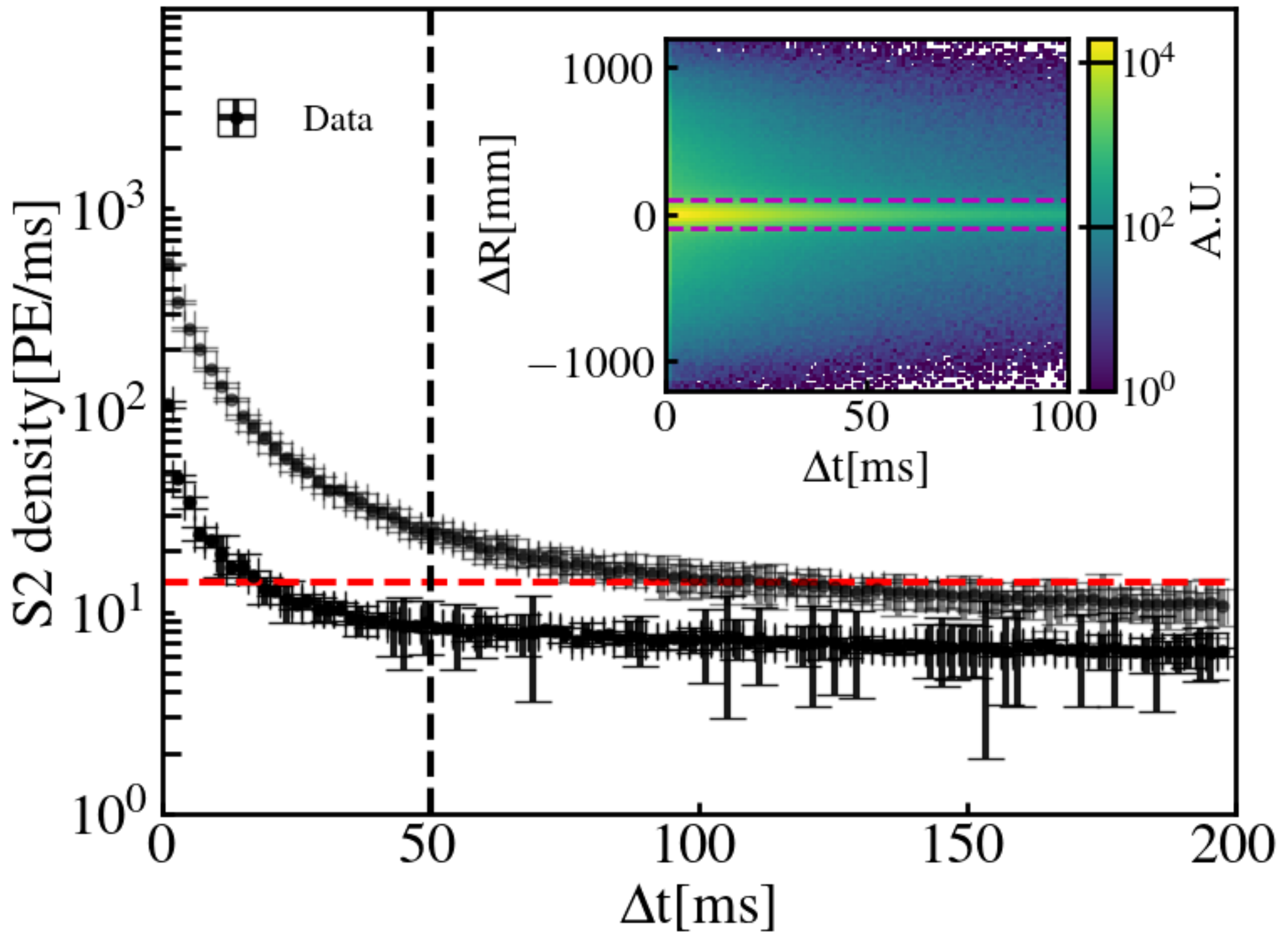
Quality cut:
- Fiducial volume
- multi-scattering veto
- S2 diffusion
- waveform cleanliness cuts

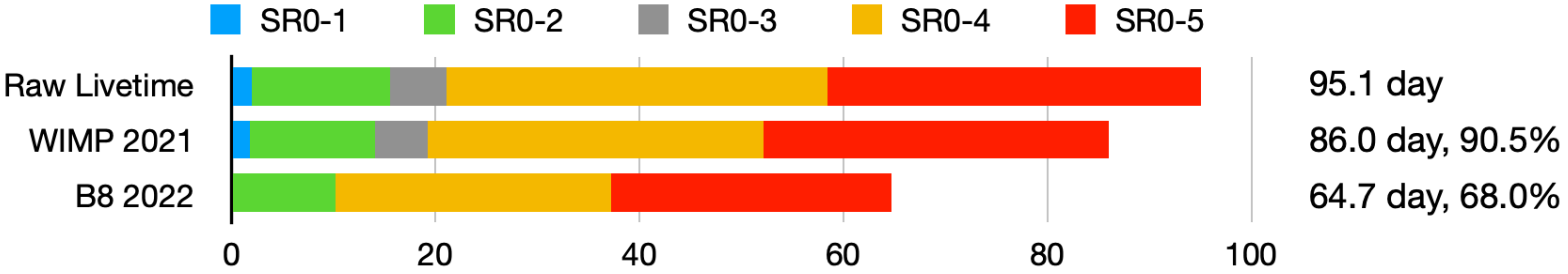
BDT cut:
- Optimize s/b

Deadtime Effect

- ~ 3% Bad data files with excessive noise
- 7 live days with excessive micro-discharge
- High-charge period induced by tail of large signals



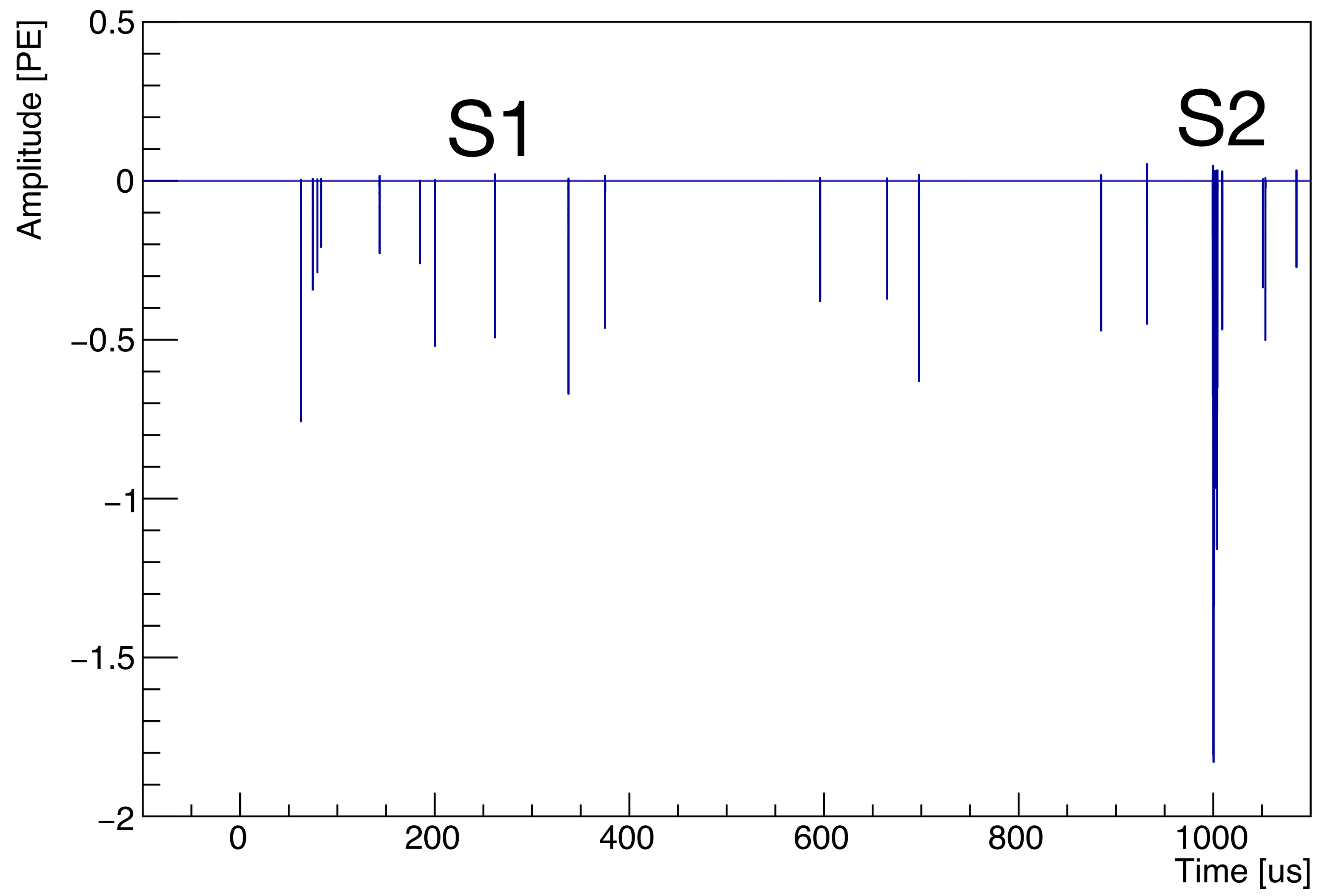




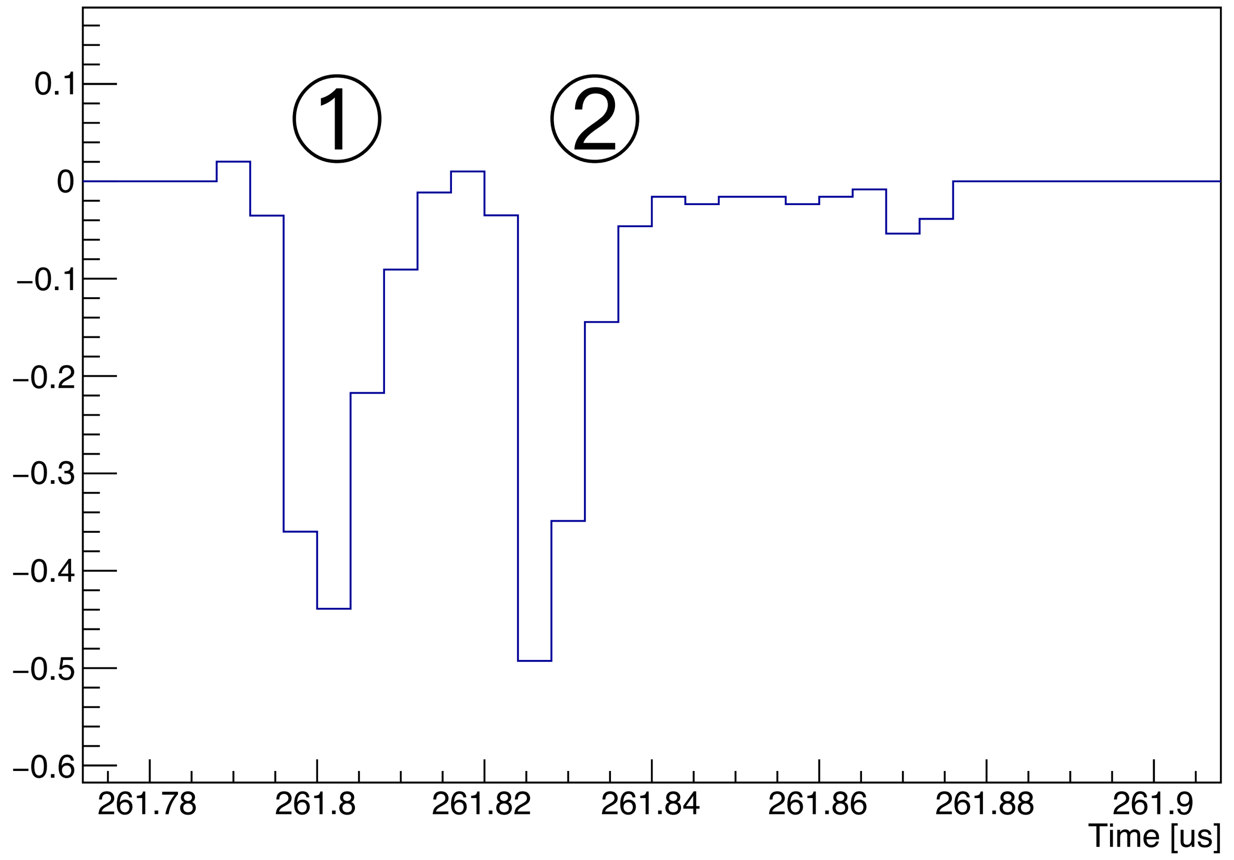
Waveform simulation

- S1: sampled from neutron S1
- S2: formed by data-driven single electrons with proper diffusion width
- Delay ionization time and amplitude measured from data
- Noise and afterpulse from data photon waveforms and and electron waveforms
- Dark rate and all noise sample from data
- Incorporate with NEST

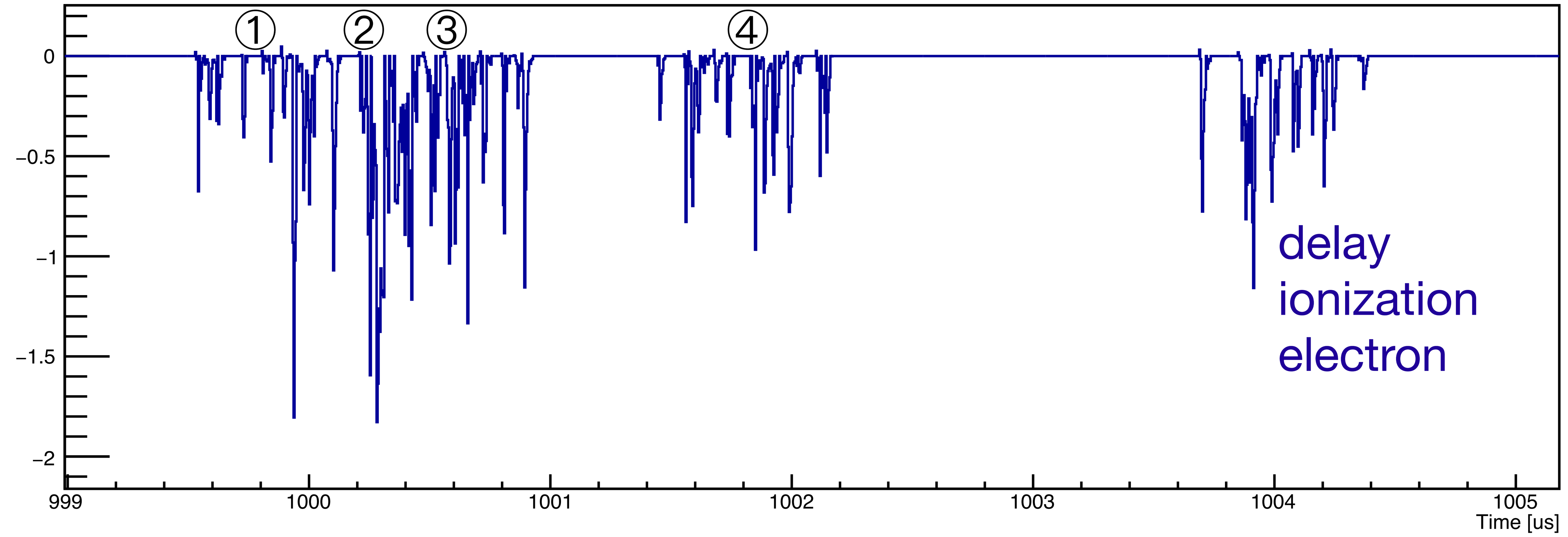
A complete simulation waveform



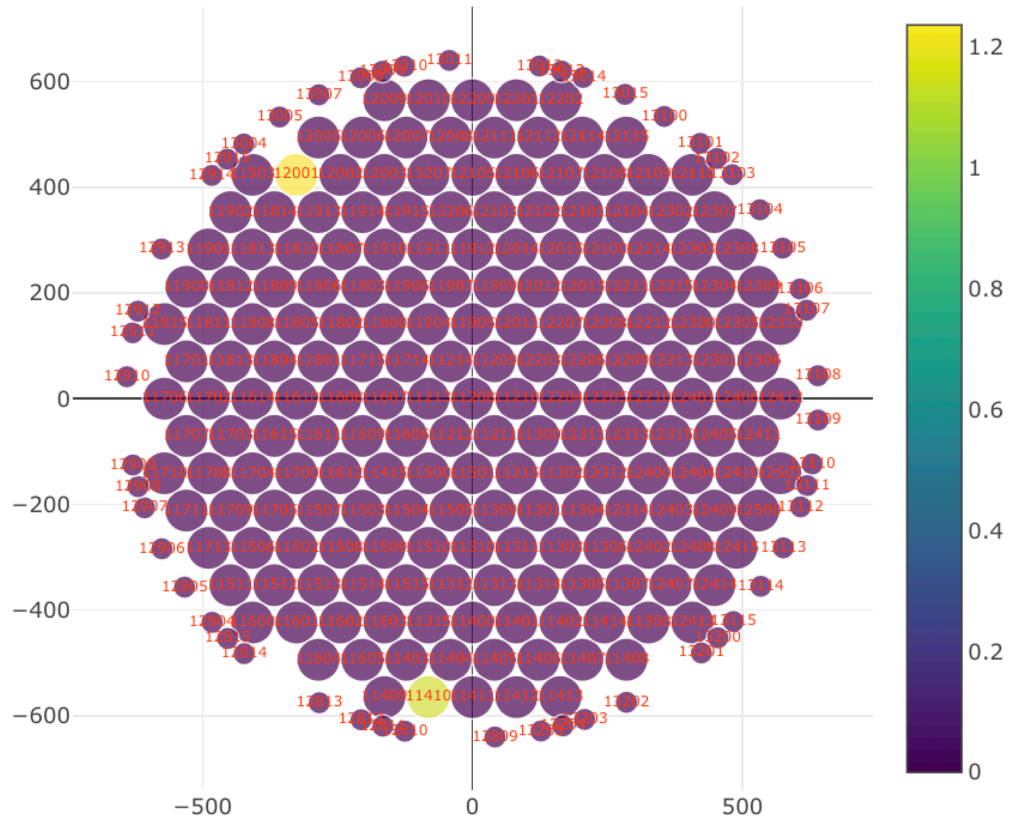
double-photon S1



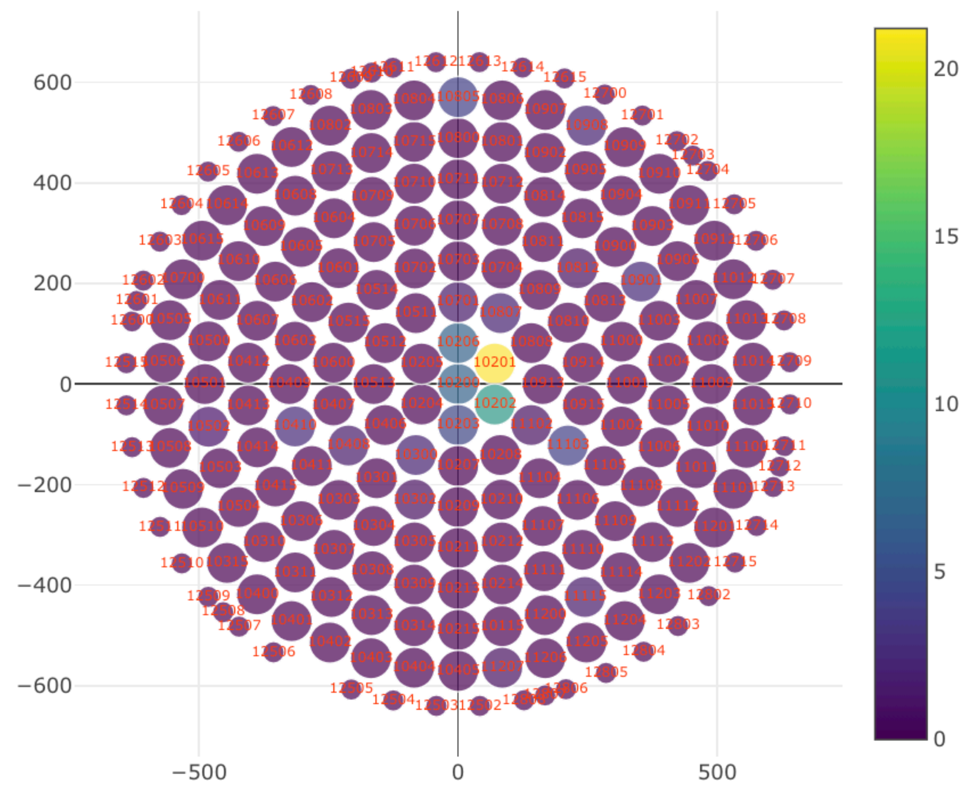
4-electron S2



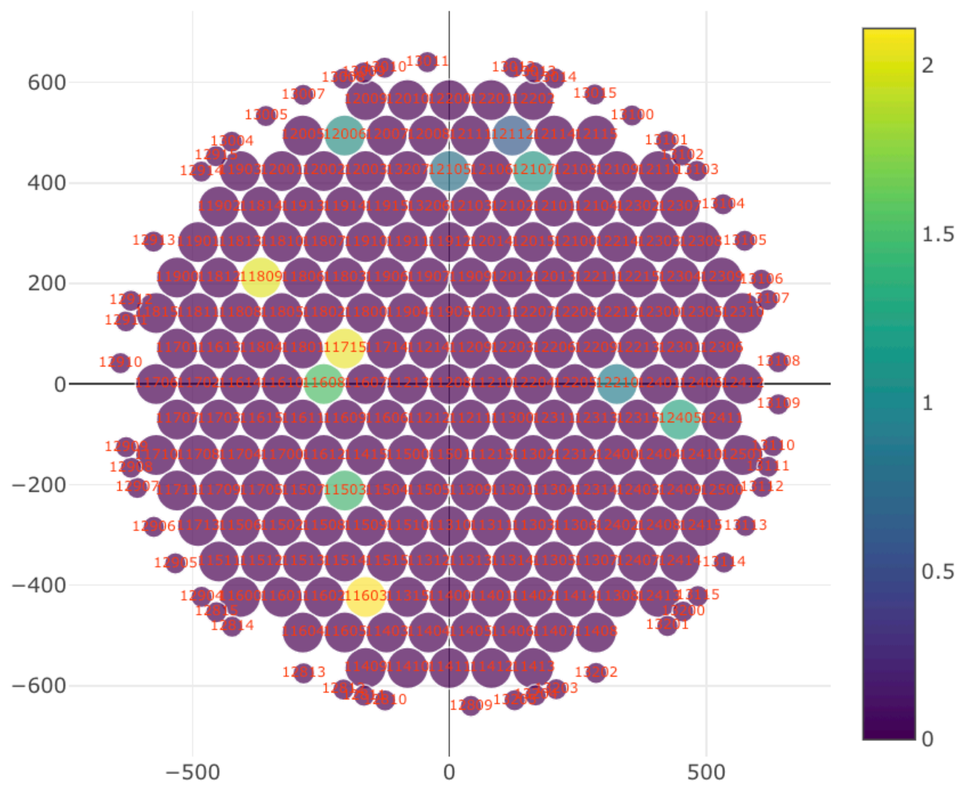
S1 pattern on the bottom array



S2 top array



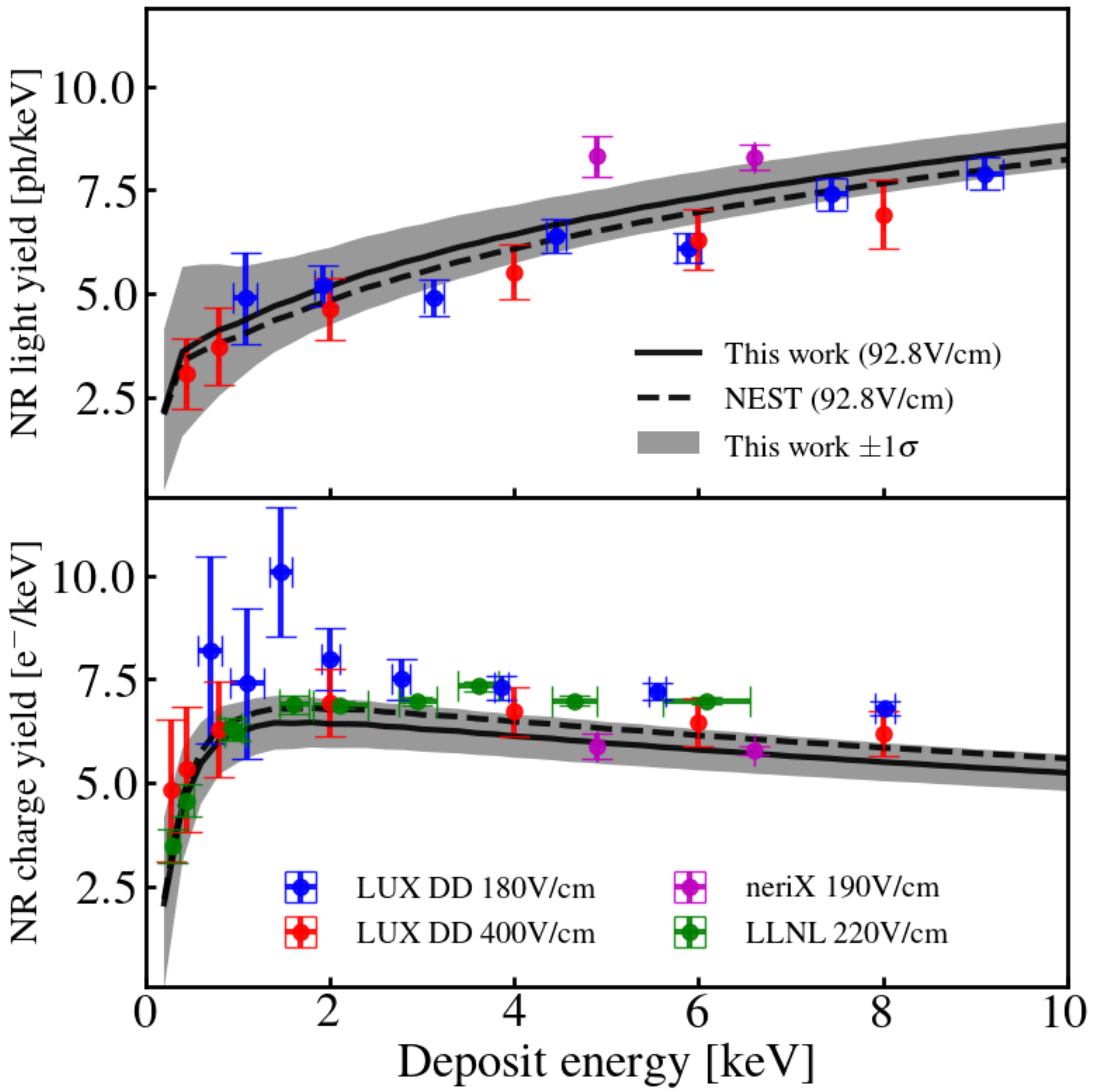
S2 bottom array



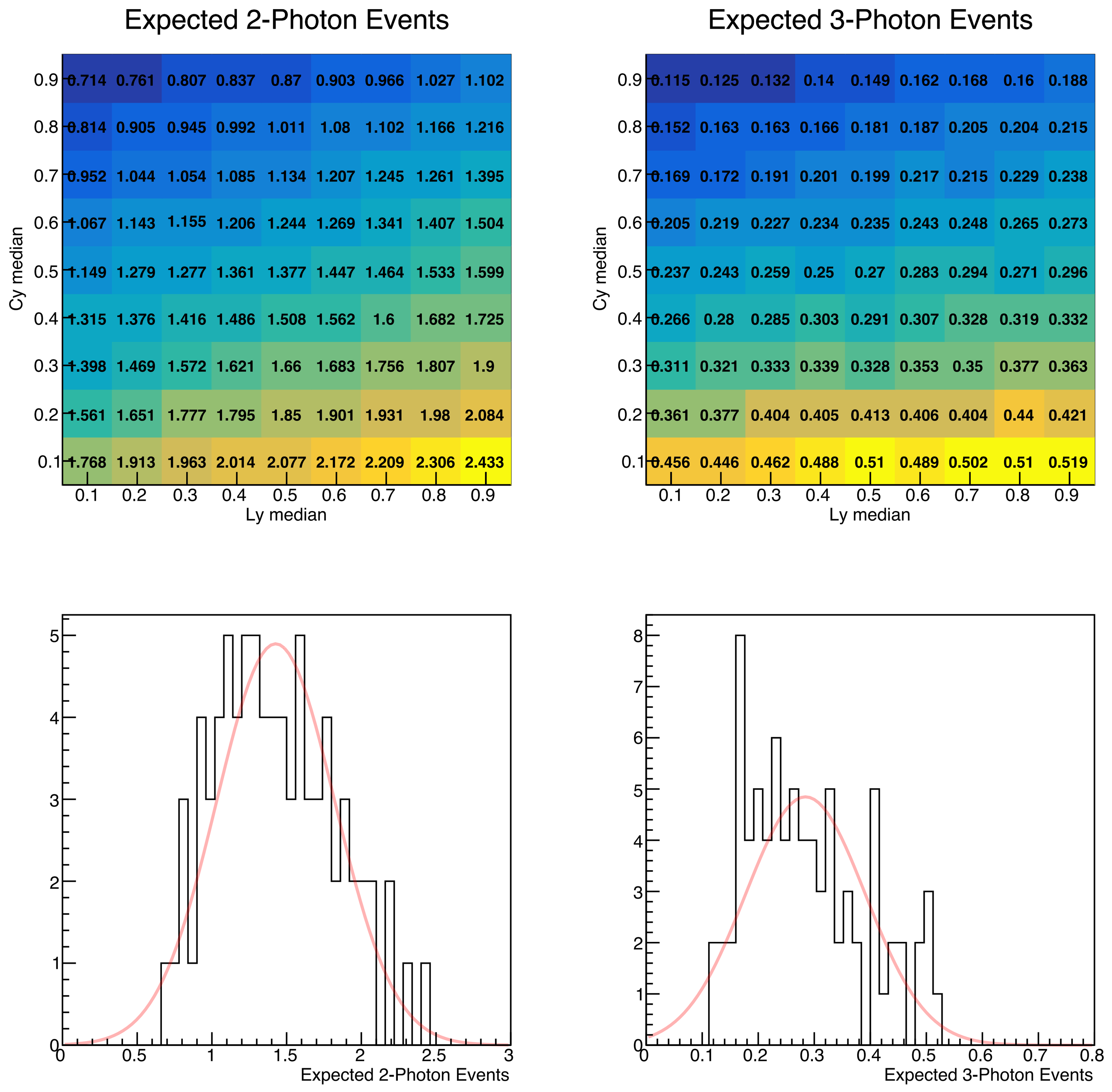
Light and Charge Yield Puzzle: Low Energy Pleateau or Break–Down?

- Nominal value fitted from WIMP 2021
- Conservative uncertainty band from NEST v2.3.6 (to cover all low-energy measurements)
- Large Ly/Cy uncertainty -> Large event rate uncertainty 30-40%

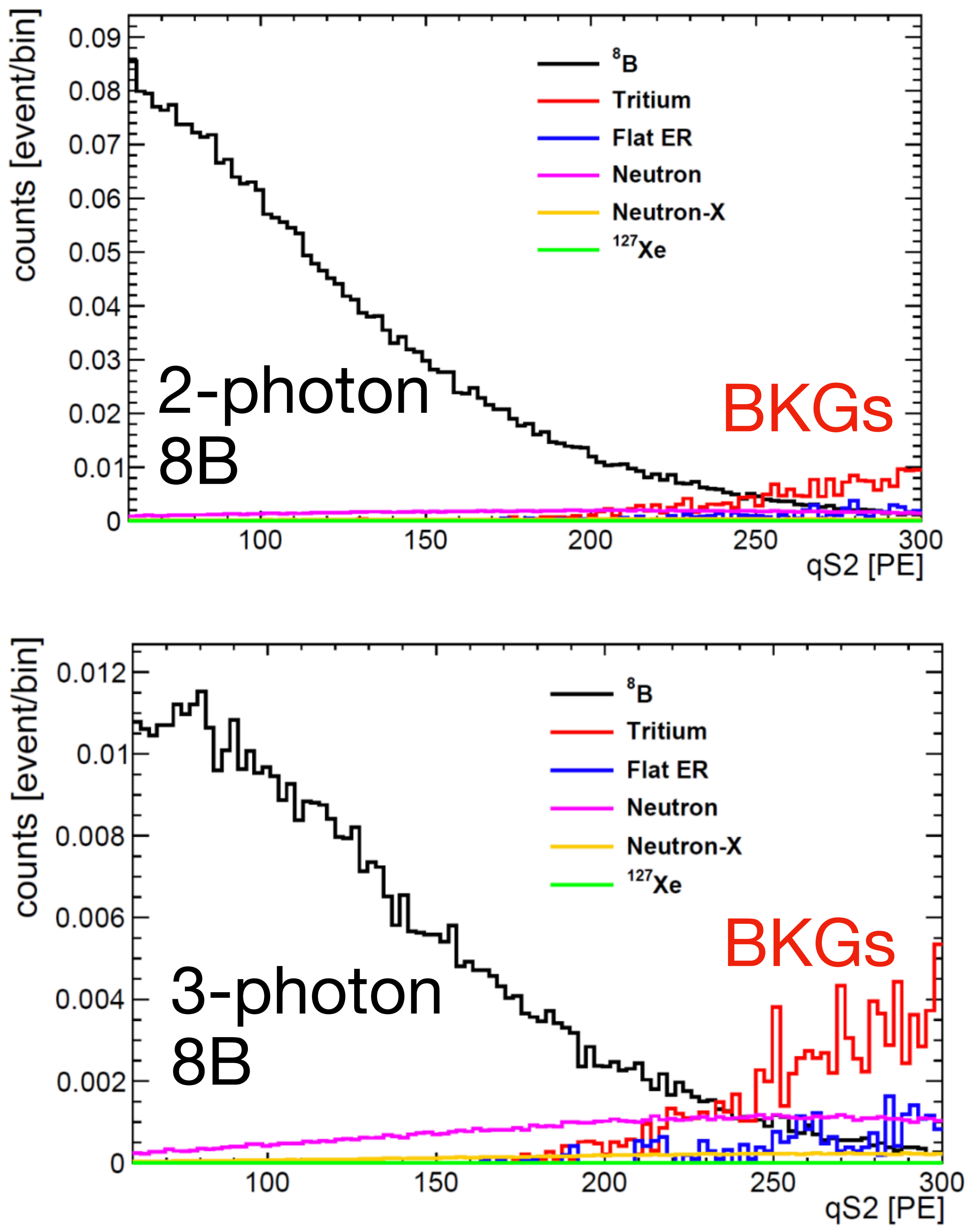
Ly, Cy, and Uncertainty



Correlation Analysis

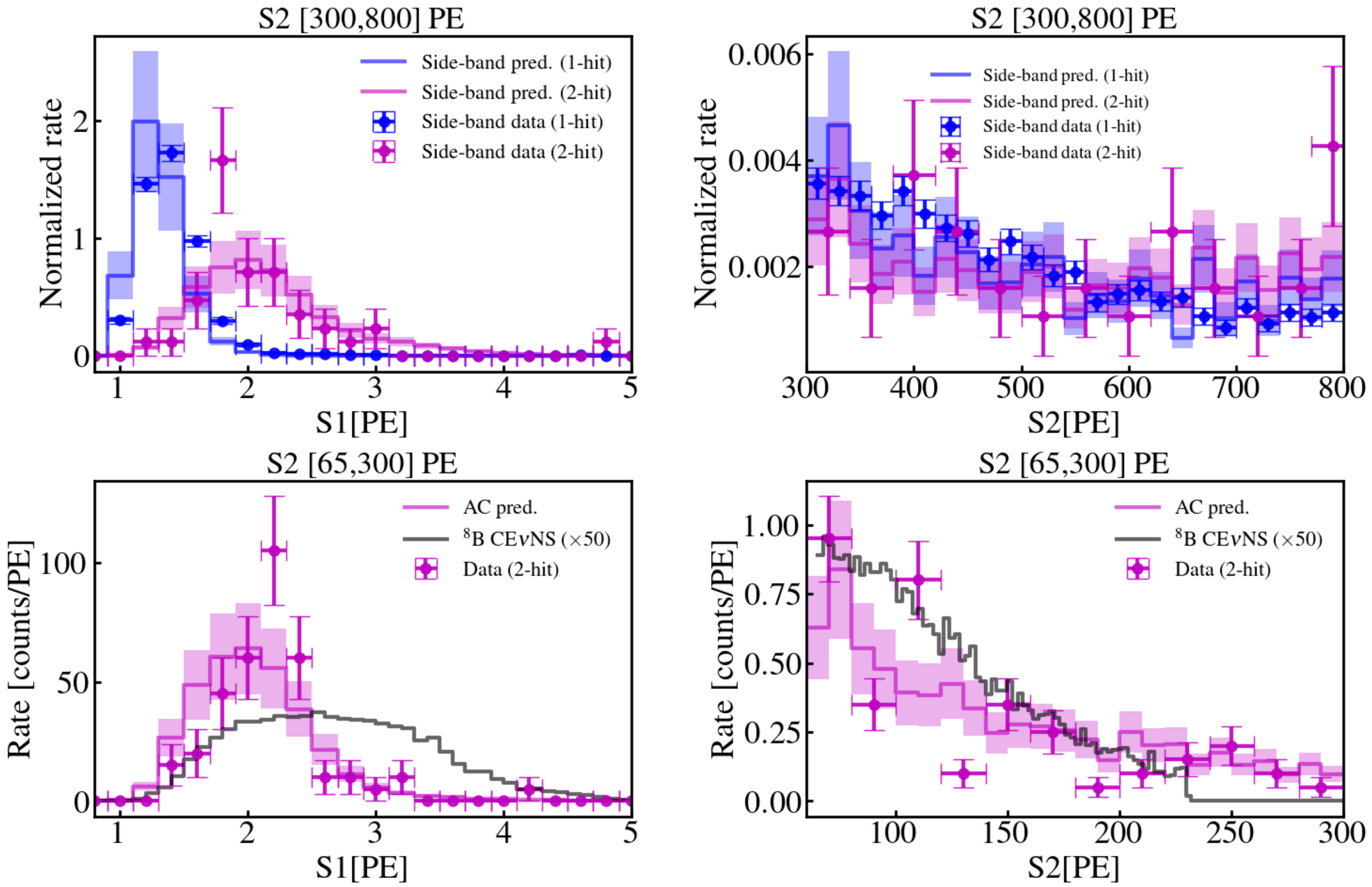


Negligible Physical Background



Accidental Background Estimation

- Enormous accidental background after lowering energy threshold
- Rate estimation + data-driven simulation → **shape prediction**
  - Accidental S2: ~ 1000 per day, are selected from 0.9-1.5ms event building
  - Accidetnal S1: 6 kHz, are picked up in 1-ms-randomly-selected waveform segment
- Apply quality cuts
- **Excellent agreement in sideband**

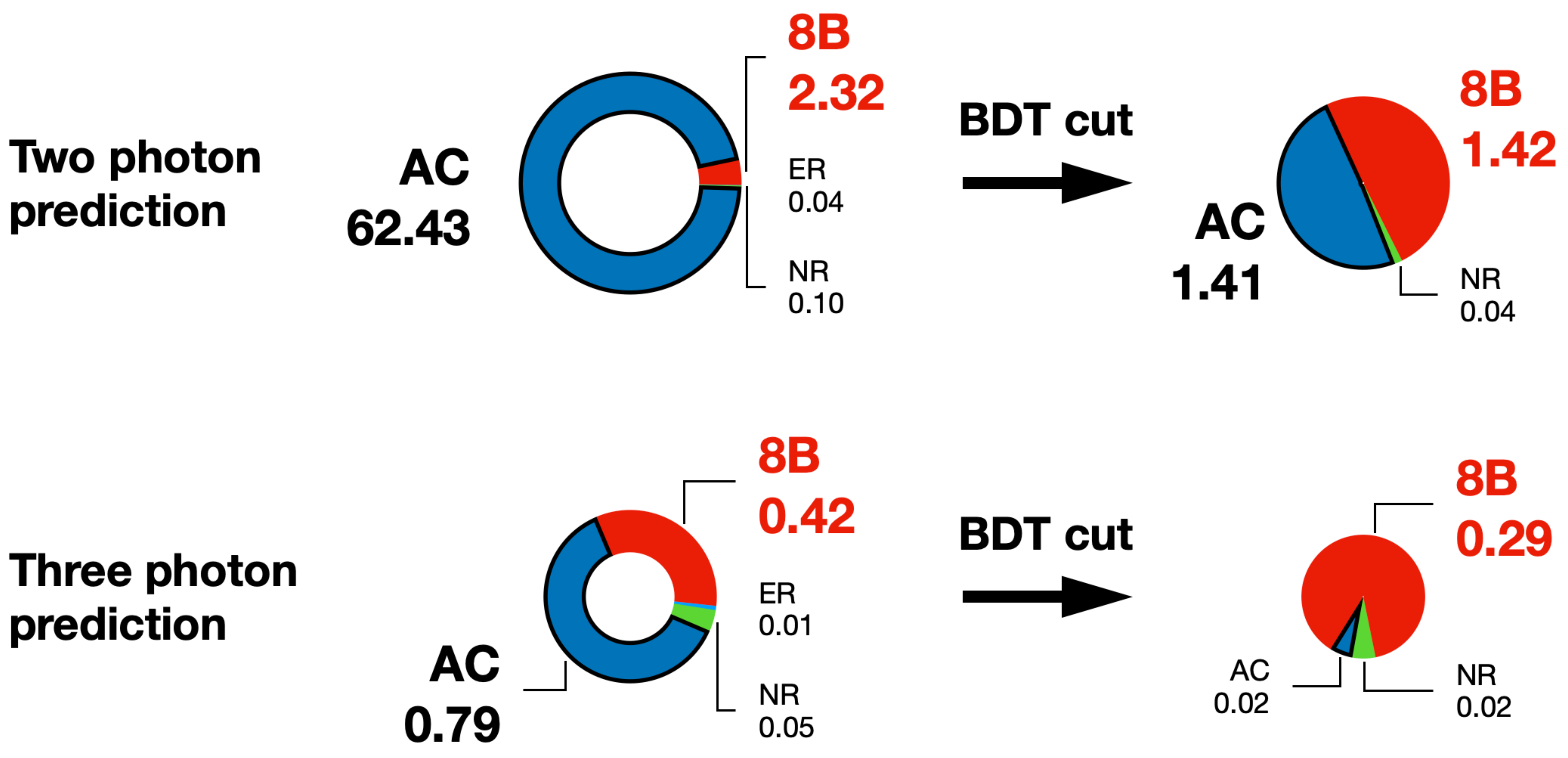


$$N_{\mathrm{AC}} = \epsilon R_{S1} R_{S2} T_{760\mu s} T_{\mathrm{duration}}$$

Number of Photons	Physical Events	Accidental Events	Total Prediction	Data
1	9.4	2060.5	2069.9	2043
2	10.1	33.8	43.9	47
3	6.9	2.2	9.1	7

Accidental Background Rejection via BDT

- **BDT:** machine learning, boosted decision tree, employed in PandaX-II: arxiv 2204.11175
- **Input variables:** related to charge, width, top-bottom asymmetry and PMT top pattern of S1 and S2s.
- **Training s/b:** $O(10^6)$ 8B event waveform simulation vs $O(10^6)$ data-driven accidental simulation
- **Optimize cut by discovery potential:** suppress **98% AC** for two photon, **95% AC** for three photon



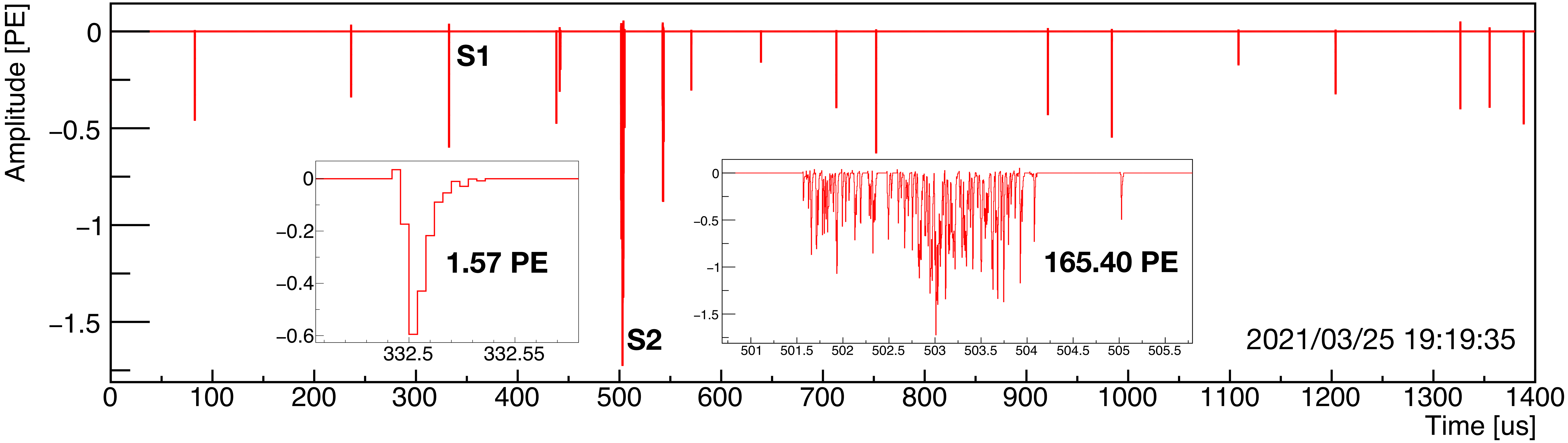
Unblinding

ROI

	ER+NR+AC	8B	**Total prediction**	**Unblind data**
Two Photon	62.57	2.32	**64.89**	**59**
Three Photon	0.85	0.42	**1.27**	**2**

ROI (BDT applied)

ER+NR+AC	8B	**Total prediction**	**Unblind data**
1.46	1.42	**2.88**	**1**
0.04	0.29	**0.33**	**0**



Statistical Interpretation

- 2-bin profile likelihood ratio analysis

$$\mathcal{L} = G(\boldsymbol{\eta}) \prod_i \frac{\lambda_i^{N_i}}{N_i!} e^{-\lambda_i} \cdot G(\boldsymbol{\theta_i})$$

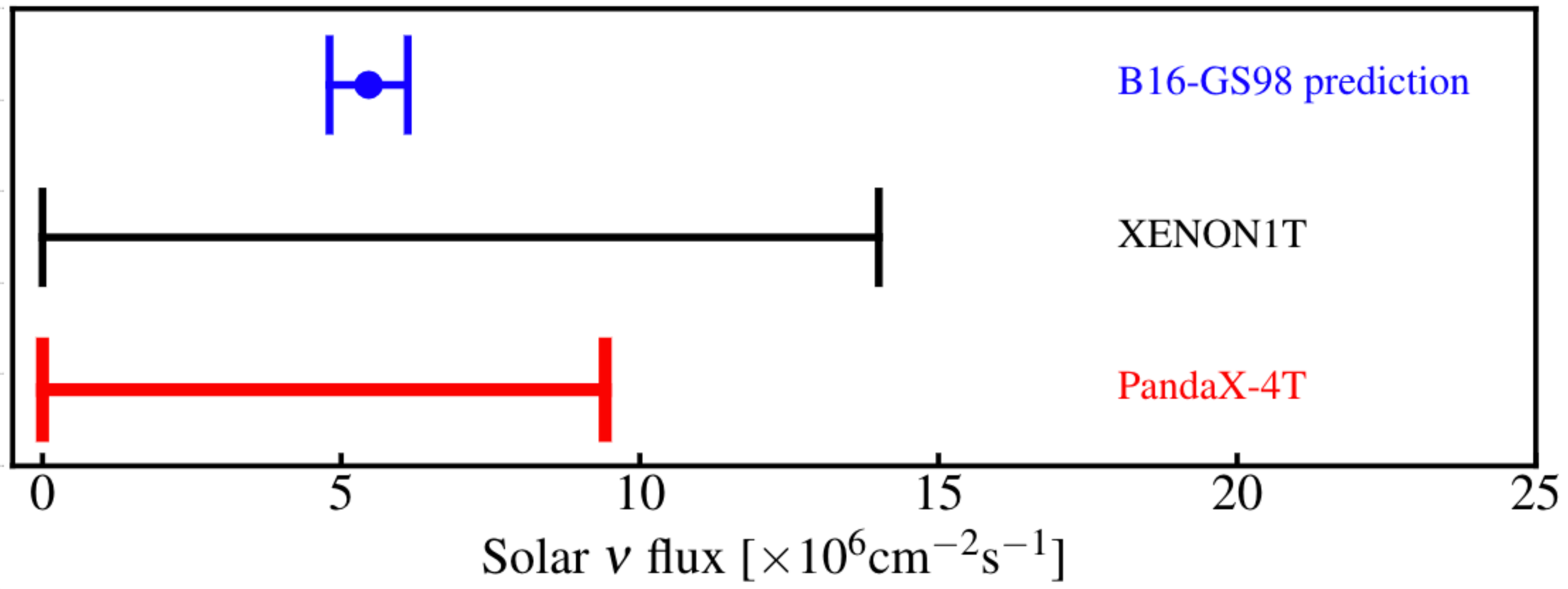
- Event rate

$$\begin{aligned}
\lambda_i^{\nu} =& (1 + f_i^{\nu}\eta_{\text{mod}})\eta_{\text{cut}}\theta_{i,\text{BDT}_s} \cdot N_{\nu} \\
&+ \eta_{\text{cut}} \cdot \theta_{i,\text{BDT}_{\text{AC}}} \cdot \eta_{\text{AC}} \cdot N_{\text{AC}} + N_{\text{other}}, \\
\lambda_i^{\chi} =& (1 + f_i^{\chi}\eta_{\text{mod}})\eta_{\text{cut}}\theta_{i,\text{BDT}_s} \cdot N_{\text{wimp}} \\
&+ (1 + f_i^{\nu}\eta_{\text{mod}})\eta_{\text{cut}}\theta_{i,\text{BDT}_s}\eta_{\text{flux}} \cdot N_{\nu} \\
&+ \eta_{\text{cut}} \cdot \theta_{i,\text{BDT}_{\text{AC}}} \cdot \eta_{\text{AC}} \cdot N_{\text{AC}} + N_{\text{other}}
\end{aligned}$$

- Nuisance parameter **conservatively**
  - **NEST induce 30%**
  - **AC induce 30%**
  - **BDT induce 25%**

	Description	mean of G	std. of G 2-hit	std. of G 3-hit
η_{mod}	NEST model scaling	0	1	
η_{AC}	AC sample scaling	1	0.30	
η_{cut}	Data selection eff. scaling	1	0.04	
η_{flux}	^{8}B flux scaling [5]	1	0.04	
θ_{i,BDT_s}	BDT scaling for signal	1	0.26	0.23
$\theta_{i,\text{BDT}_{\text{AC}}}$	BDT scaling for AC	1	0.19	0.18

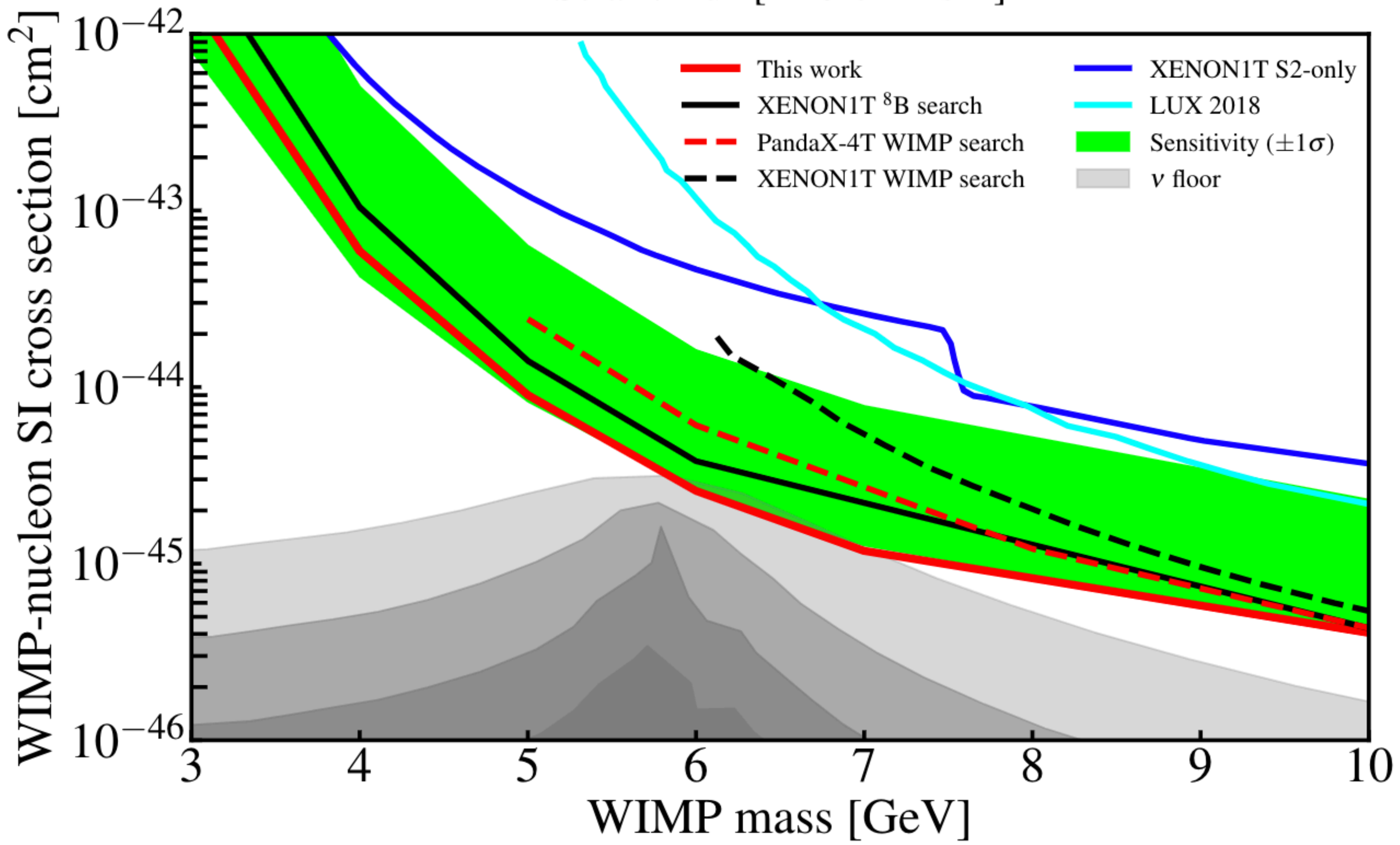
- Leading constrain on solar 8B flux (via CEvNS) and 3-10 GeV WIMP



SSM prediction

XENON1T 2021

This work

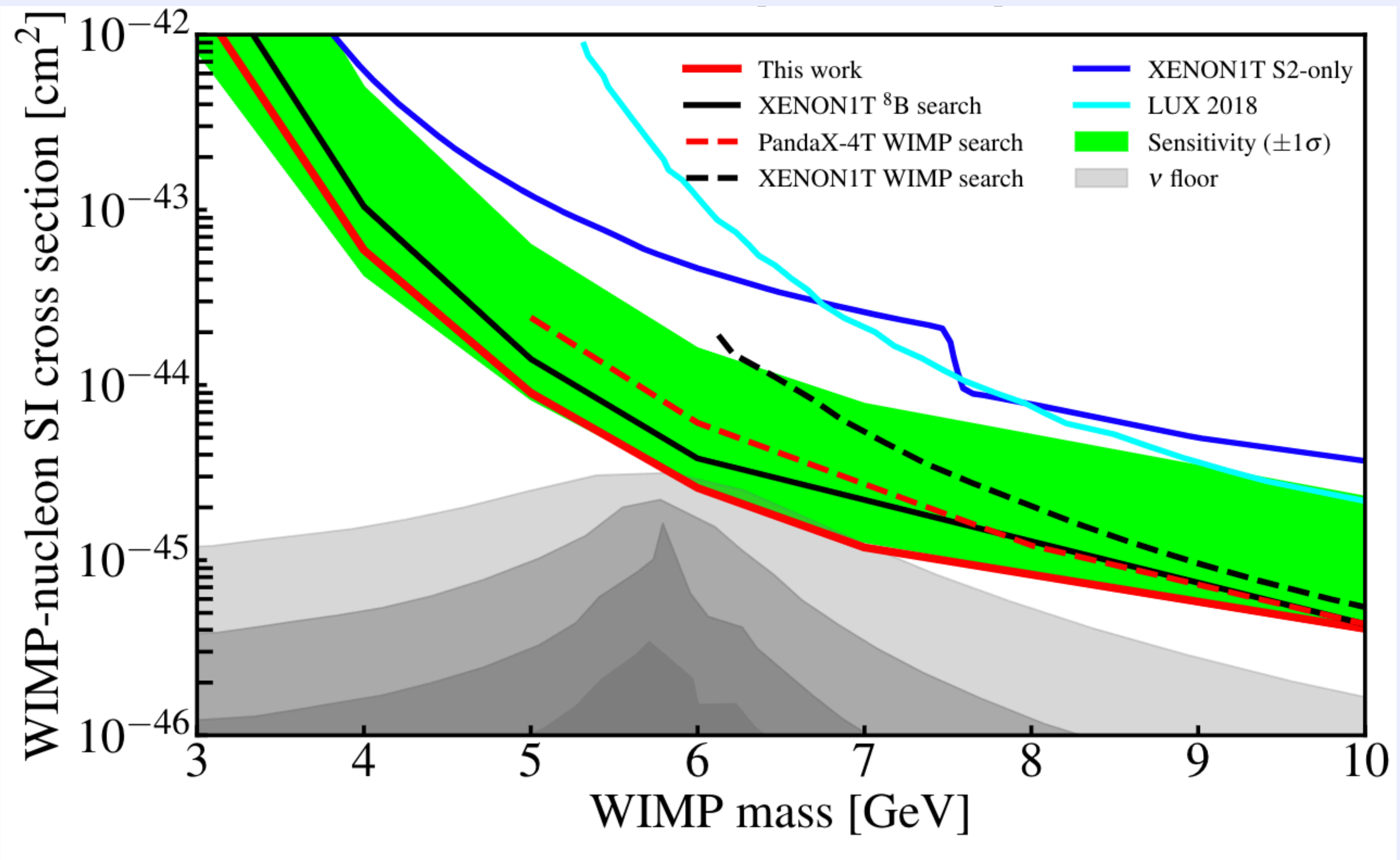


This work

neutrino floor

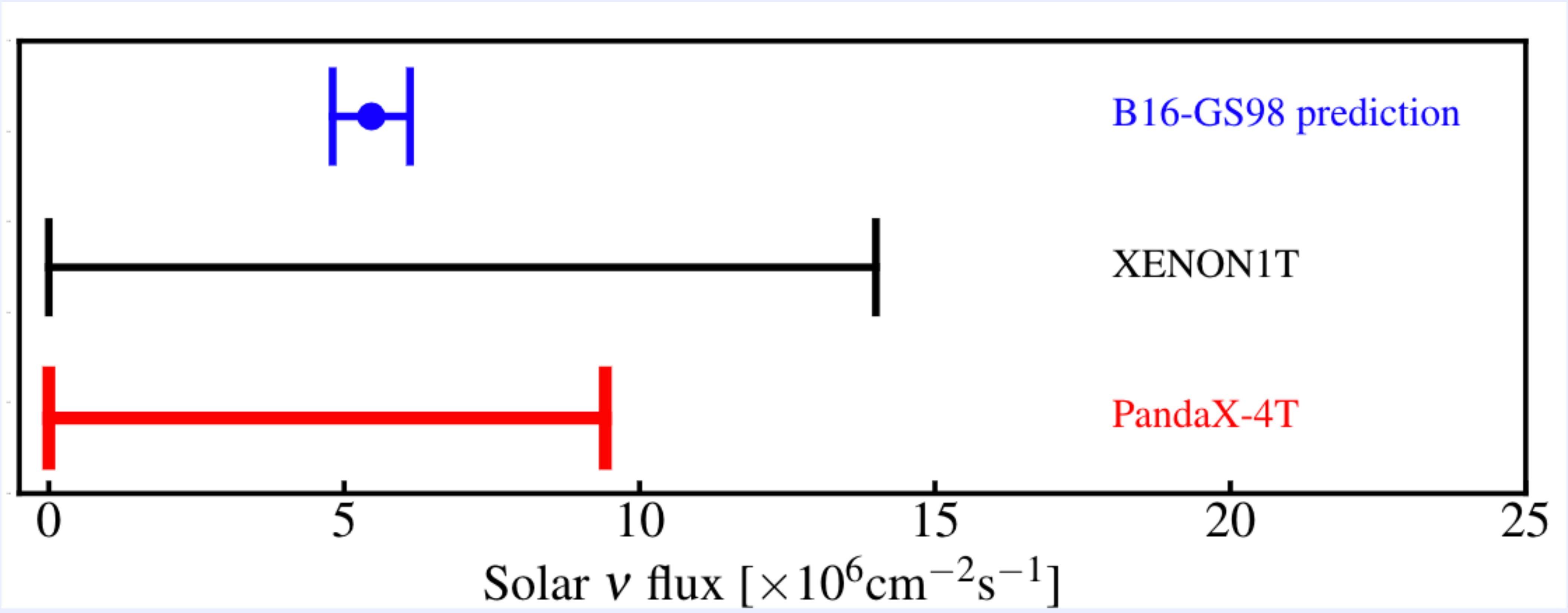
Discussion and Summary

- **For low-mass WIMP and other DM candidates**



- **Novel DM analysis tech**
- **Unprecedented sensitivity**
- **Low mass enhancement for LXe experiments**

- **For solar neutrino via CEvNS**



- **The eve of the discovery**
- **Hundreds of events in next-generation detector PandaX-30T**
- **Understanding solar metallicity and 8B flux**

- **For BSM neutrino physics**
- **This result can be cast into various parameters space of neutrino interactions**